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SOME PRINCIPLES INVOLVED IN THE CONSTRUCTION OF UNAMPLIFIED CONTROL SYSTEMS FOR ELECTROMECHANICAL MANIPULATORS

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ABSTRACT. The requirements for manipulator control systems are listed. General principles involved in the construction of unamplified reversible follow-up systems using selsyns are discussed.

The efficiency of the operator-manipulator system is determined by the manipulator's control system. Manipulator control systems should satisfy the following requirements in order to perform a wide range of operations for minimum expenditure of the operator's strength: /56

1. Ensure that the slave "arms" copy the movements of the master "arms" with the necessary speeds and accelerations.

2. Create conditions for the operator to control the forces applied to the manipulator slave elements completely, or partially, to scale, for medium and large load-carrying capacity manipulators.

3. Ensure a minimum expenditure of the operator's muscular energy when working with the manipulator.

These requirements are satisfied by control systems with active force reflection, otherwise known as reversible follow-up systems (RFS). A number of schemes for reversible follow-up systems have been developed in the Soviet Union and abroad [1, 2] which, as a rule, are rather complex automatic control systems using a combination of two transformer follow-up systems. One is for position following, the other for force following. Complicated correction mechanisms are required for quality operation of a reversible follow-up system such as this. Thus, a control system with one degree of manipulator mobility includes quite complicated amplifier-converter electronic equipment. A manipulator set (two master and two slave arms) with seven degrees of mobility is controlled by 14 RFS.

The use of complicated equipment, made up of many elements, creates difficulties in providing failure-free operation of a manipulator, especially in those branches of industry where a breakdown, or failure, in manipulator control can be disastrous. Manipulators with the simplest possible control

systems must be built for these branches.

Such systems, obviously, must be built of elements that will work when signals are strong enough and thus will not require amplifiers. Such reversible follow-up systems as unamplified manipulator control systems can be characterized in accordance with this criterion. The best example of an unamplified reversible follow-up system is a selsyn-type synchronous indicator follow-up system [3]. /57

This system has position reversibility. The selsyn rotors will match regardless of the shaft to which the controlling action is applied; to the shaft of the selsyn transmitter, or to the shaft of the selsyn receiver. The indicator system also has the property of moment reversibility: a moment applied to the shaft of the selsyn transmitter is reproduced at the shaft of the selsyn receiver, and vice versa. The error in the position of receiver and transmitter shafts is determined by the magnitude of the synchronizing moment, equal to the difference in the moments applied to these shafts.

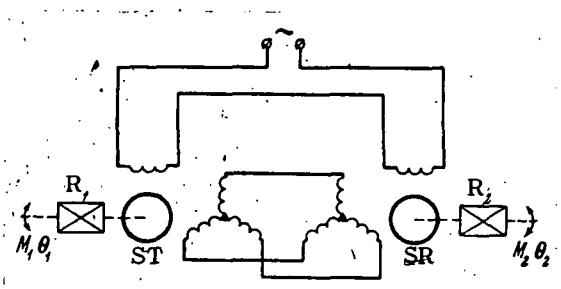

Figure 1. A reversible follow-up system using power selsysn in the indicator mode.

The magnitude of a system's maximum synchronizing moment when the most powerful indicator selsyns (for example, the ND-521 transmitter NS-501 receiver) are used is 2.6 kgf-cm, which is clearly inadequate if these systems are to be used as manipulator control systems.

Our industry has produced SS-195 type power selsyns with a specific synchronizing moment of 1.5 cm/deg for power synchronous follow-up systems. However, they cannot be used in a manipulator because each such selsyn weighs more than 60 kg. Thus, lack of power selsyns with the necessary power ratings and, at the same time, acceptable size substantially limits the possibility of using selsyn synchronous follow-up systems for manipulator control.

Of the indicator seslyns produced by our industry, the ND-521 is the most suitable for operation in the power mode. A follow-up system made up of a pair of these selsyns (the ND-521 is also used as the receiver) is stable and has completely satisfactory static and dynamic characteristics. The system's

maximum synchronizing moment is 12 kgf-cm when the shafts of the transmitter and receiver are mismatched by 70 degrees. Reduction gears R_1 and R_2 (Figure 1), must be installed between the shaft of the selsyn transmitter and the master element, and, correspondingly, between the shaft of the selsyn receiver and the slave element in order to use this particular system, even with a light-duty manipulator. This increases the synchronizing moment and the accuracy with which the system settles out by a factor of i (where i is the reduction gear ratio), while at the same time raising the possibility that the shafts in the system will make a false match in 360: i positions, and that there will be considerable distortion in the transmission of moments from the slave to the master because of friction and inertia in the reduction gears and selsyns. The position of the slave "arms" is monitored visually by the operator, so the possibility of a false match between the manipulator's master and slave "arms" presents no danger. The operator can always match their positions before beginning work, as well as while the work is going on.

To clarify the properties of the system as it transmits force, let us consider the equation of moments when the motion of the input shaft with constant acceleration is given: 58

$$M_1 = M_2 + M_{Fr1} + M_{Fr2} + (I_1 + I_2)\frac{d^2\Theta_1}{dt^2},$$

where

M_1 and M_2 are the moments on the master and slave shafts, respectively;

M_{Fr1} and M_{Fr2} are the selsyn and reduction gear moments of friction normalized to the input shaft;

I_1 and I_2 are the selsyn rotor and gear link moments of inertia normalized from the selsyn shafts to the system's input and output shafts;

Θ_1 is the angle imparted by the shaft of the master mechanism.

The equation shows that the operator, in addition to becoming aware of the useful signal, equal to the applied load moment, M_2, also will become aware of the slave and master mechanism gearing moments of friction, M_{Fr2} and M_{Fr1}, normalized to the master shaft, and the normalized dynamic moments attributable to the inertia in the selsyn rotors and in the gearing associated with them $(I_1 + I_2)\, d^2\Theta_1/dt_2$.

The magnitudes of the normalized friction moments are directly dependent on the reduction gear ratio, i, and the normalized dynamic moments will be directly proportional to the square of the gear ratio. Harmful moments attributable to the forces of friction and inertia can be several times the load moment, M_2, applied to the slave element when reduction is great.

The operator then will find it difficult to monitor the forces applied to the slave element and will in addition, have to exert a great deal of force even to control an unloaded manipulator. The effect of the harmful moments on the operator's arm can be reduced, and control of the manipulator can be facilitated, by the introduction of proportionality in the transmission of the moment from the slave to the master element.

Now the equation of moments will be

$$M_1 = M_{Fr1} + m(M_2 + M_{Fr2}) + (I_1 + mI_2)\frac{d^2\Theta_1}{dt^2},$$

where m is the proportionality factor.

Let us, in order to explain how porportional transmission of moment in a synchronous indicator follow-up system is possible, consider the equation of moments for a selsyn transmitter and receiver [3].

The moment of the shaft of the selsyn transmitter (ST) is

$$M_T = \frac{3}{2} \cdot \frac{1{,}02 \cdot 10^4}{\omega} \cdot \frac{E_{sT}E_{sR}}{2Z} \cdot \frac{W_T W_R}{W_{sT} W_{sR}} \sin(\alpha - \beta) \times \left[\cos(\varphi_R - \varphi_T)\frac{X}{Z} - \sin(\varphi_R - \varphi_T)\frac{R}{Z}\right]. \quad (1)$$

The moment on the shaft of the selsyn receiver (SR) is

$$M_T = \frac{3}{2} \cdot \frac{1{,}02 \cdot 10^4}{\omega} \cdot \frac{E_{sT}E_{sR}}{2Z} \cdot \frac{W_T W_r}{W_{sT} W_{sR}} \sin(\beta - \alpha) \times \left[\cos(\varphi_R - \varphi_T)\frac{X}{Z} + \sin(\varphi_R - \varphi_T)\frac{R}{Z}\right], \quad (2)$$

where

E_{sT} is the actual value, for the angle, of the maximum emf induced in the transmitter synchronization phase;

E_{sR} is the same for the receiver;

Z is the modulus of complex circuit resistance for each pair of series-connected transmitter and receiver phases;

W_{sT} is the effective number of turns in the transmitter excitation winding;

W_{sR} is the same for the receiver;

α is the transmitter angle of rotation;

β is the receiver angle of rotation;

ω is the angular frequency;

φ_R is the receiver supply voltage time phase;

φ_T is the transmitter supply voltage time phase.

As may be seen from Eqs. (1) and (2), the moments on transmitter and receiver are equal in absolute magnitude when the supply is in-phase.

If the receiver and transmitter are supplied with voltages shifted in phase, the moment on the receiver will be greater than that on the transmitter, that is, the moment transmitted from receiver to transmitter will be in proportion.

The following condition should be satisfied in order to provide specified proportionality when X = R:

Figure 2. Reversible follow-up system using power selsyns with proportional moment.

The shift in the phase of the voltage supplied to the field winding of one selsyn relative to another is achieved by connecting capitance, C, in series with one of the field windings.

The synchronous follow-up system using ND-521 power selsyns with proportional moment described above (Figure 2) was used to control the links of a manipulator with a 5 kg load capacity. The system provided manipulator efficiency with the following technical data (motion, rocking of the hand): (1) load capacity

5 kgf; (2) proportionality in the transmission of moment from slave to control element 1:1; (3) maximum speed of end of working tool 685 mm/sec; (4) maximum acceleration 2690 mm/sec^2; (5) touching force 600 gf.

However, this scheme cannot be used for high capacity manipulators (severe distortions in the forces being monitored because of harmful moments of inertia and friction, etc).

A scheme has been developed for medium capacity manipulators (up to 10 kg), in which the harmful moments from forces of friction and inertia, are largely balanced at the shaft of the controlling mechanism by a special follow-up system using a motosyn (a combined selsyn-motor) [5].

The combined selsyn-motor was invented by D. V. Svecharnik [4]. The SDS-3M, an industrial type combined selsyn-motor, was developed by the "Teplopribor" Scientific Research Institute (Moscow) and put into production [4]. Figure 3 is a longitudinal cross section of the motor. The principal components are the stator 1, internal rotor 2, and hollow rotor 3. The stator of the SDS-3M motor is similar to the stator of the ND-521 selsyn. The hollow aluminum rotor can turn in bearings with respect to the internal rotor shaft. The internal rotor winding is single-phase, that of the stator three-phase. All three phases of the motor can be sued when the motor is used in a follow-up system as a combined selsyn-motor, in which case the stator winding is the synchronization winding. Figure 4 shows how the SDS-3M motor is connected to drive an electromechanical manipulator. Only two phases of the stator winding, connected in series with a condenser, are used. The hollow rotor motor depends /60 on the angle of rotation of the internal rotor relative to the stator when the power supply to the motor is as shown in Figure 4. When the winding axes coincide there is no rotating magnetic field in the gap, and the hollow rotor is stationary. A rotating magnetic field is created in the gap with rotation of the internal rotor and the hollow rotor begins to rotate. The hollow rotor moment and speed depend on the absolute magnitude of the angle of rotation and reach maxima at rotation of approximately 80-100°. The direction of rotation, and the sign of the moment, depend on the sign of the angle of rotation.

The SDS-3M motosyn has the following technical characteristics: maximum SDS-3M motor starting torque exceeds 4000 g-cm; idling speed is approximately

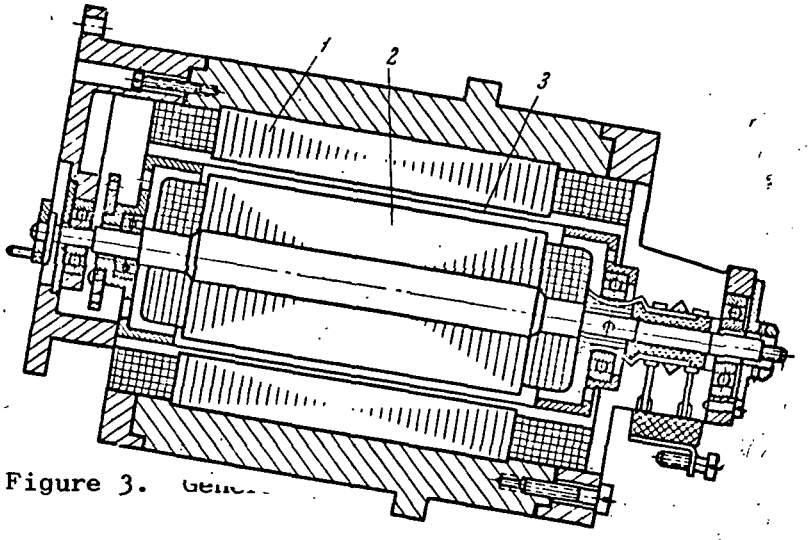

Figure 3. Gene...

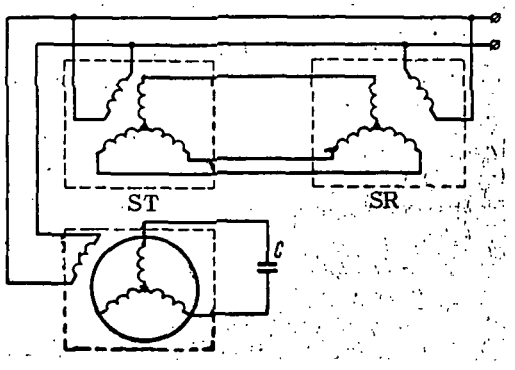

Figure 4. Electric circuit of an unamplified reversible follow-up system with a motosyn.

2700 rpm. The ...cal characteristic (moment in terms of speed) decreases monotonously with a nonlinearity of 25% when the angle of rotation of the internal rotor is $\Theta = 90°$. The motor has satisfactory regulation characteristics. The machine's utilization factor (the ratio of power realized in the form of starting torque to the active power required by the machine when starting) is 77.8% equal to that of conventional motors of corresponding size with a hollow rotor operating "all out." The SDS-3M can operate "all out" with a moment of 400 gf-cm ($\Theta = 70°$) with a 30% connection time. Intensive air-cooling of the motor is necessary for normal operation /61 because continuous connection in the start mode for 30 minutes will cause the internal rotor winding to heat to 130°C.

The stator and rotor winding supply is 45 V 50 Hz, and the capacitance of the condensor in the stator winding is 300 μf.

Figures 4 and 5 show the electrical and kinematic diagrams of a control system with one degree of meanipulator mobility using motosyns. The slave mechanism, I (see Figure 5), includes selsyn receiver 1, reduction gear 2, and output shaft 3. The control mechanism, II, consists of selsyn-transmitter 4, reduction gear 5, and flexible coupling 6, connected through geared transmission 7 to solid rotor 9 of SDS-3M motor 10. The solid rotor shaft is coupled to system input shaft 14. The coupling is connected to motor housing 10 on the other side

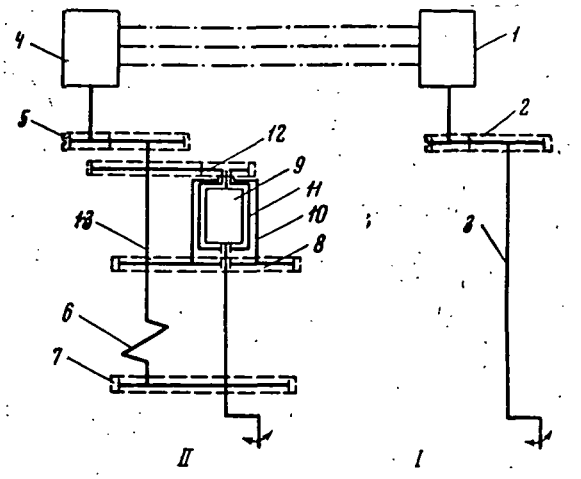

Figure 5. Kinematic diagram of an unamplified RFS with a motosyn.

through geared transmission 8. The hollow rotor of the SDS-3M is connected through geared transmission 12 to drive output shaft 13. Electrically (see Figure 4) the selsyns (transmitter ST and receiver SR) are connected in what is the conventional arrangement for selsyns operating in the indicator mode. The SDS-3M motor rotor winding is connected to the net, and the stator winding is connected to the net in series with condenser C, selected to create a time shift of 90° in the rotor and stator winding phases. A closed proportional follow-up in which the solid rotor follows the SDS-3M stator results when there is closure of the stator of the SDS-3M and its hollow rotor by a mechanical transmission.

The system operates as follows. Flexible coupling 6 is deformed when drive input shaft 14 turns (see Figure 5) and solid rotor 9 of the SDS-3M motor is mismatched relative to its stator 10. Hollow rotor 11 now turns, turning reduction gear 5 and selsyn transmitter 4 through geared transmission 12. Friction and inertia in this part of the kinematic chain are balanced simultaneously matching the SDS-3M motor stator and its solid rotor 9 through transmission 8. Selsyn receiver 1 matches the slave mechanism output shaft with control mechanism input shaft 14. This is how the slave element tracks the position of the master.

Moment M_2, applied to the slave mechanism shaft, is transmitted by selsyn transmitter 4 through reduction gear 5, flexible coupling 6, and geared transmission 7 to input shaft 14. Simultaneously, the SDS-3M motor stator is mismatched with its solid rotor 9 through geared transmission 8 because of deformation of flexible coupling 6. The result is to set up a counteracting moment, M_k, on shaft 13. Chaning the SDS-3M supply voltage, the gear ratio of transmission 12, and the stiffness of flexible coupling 6, we can make this counteracting moment, M_k, equal to the friction moment of the kinematic chain from the hollow rotor of the SDS-3M motor to selsyn transmitter 4 and to the friction moment of the kinematic chain of the slave mechanism normalized to shaft 13. 62

The proportion in which the moment is transmitted then will be close to unity, $M_1 = M_2$, or, in order for moment M_k to exceed the magnitudes of the harmful moments, $M_1 < M_2$, that is, the moment applied to shaft 3 of the slave mechanism will be transmitted to shaft 14 of the control mechanism in a definite proportion.

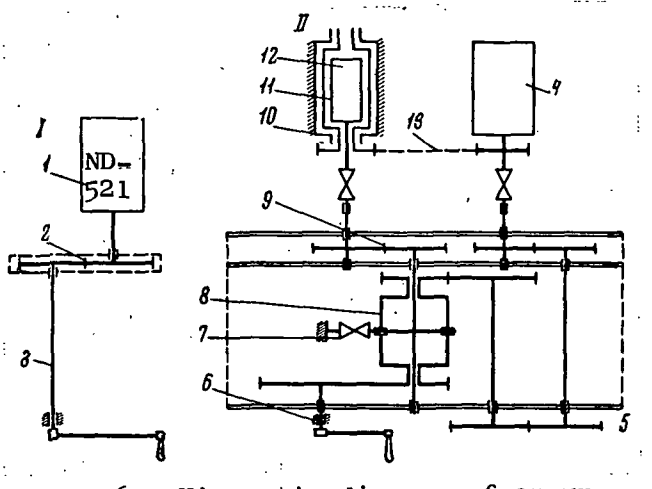

Figure 6. Kinematic diagram of an unamplified RFS with a motosyn. Static variant. 1 - selsyn transmitter; 2 - slave mechanism reduction gear; 3 - system input shaft; 4 - selsyn receiver; 5 - master mechanism reduction gear; 6 - system output shaft; 7 - flexible coupling; 8 - differential; 9 - geared transmission; 10 - SDS motorsyn stator; 11 - motosyn hollow rotor; 12 - motosyn solid rotor; 13 - geared transmission.

There are design problems involved in the realization of the kinematic scheme discusssed when applied to manipulators. Then too, slip rings and brushes must be installed to bring the power supply to the rotating stator of the motosyn, reducing control system reliability. The control system shown in Figure 6 is devoid of the shortcomings noted above. Here the SDS stator is fixed and matching of the balancing follow-up system is accomplished through a differential, which facilitates the structural configuration of the manipulator gear box and reduces electrical contacts in the circuit to a minimum.

This control system has been built for a 10 kgf capacity manipulator. The manipulator is highly dependable in operation, is simple in design and operation, yet has such completely satisfactory technical characteristics as swinging motion of the "hand" for example. The mean linear speed of the tip of the operating tool is 370 mm/sec. Maximum acceleration of the tip of the operating tool is 1540 mm/sec^2. The touching force of the unloaded manipulator is 700 fg. The proportionality in the transmission of force is 1:1.7.

REFERENCES

1. Sirazitdinov, B. G., Zubkov, D. I., "A Reversible Follow-up System for Transmission of Forces and Movements Over a Distance," Izv. VUZov Priborostroyeniye, No. 3, 1961.

2. Masakudu, E., Akira, K., "Servomanipulators," Keysoku-to seyge, No. 7, 1963.

3. Svecharnik, D. V., Sel'siny i ikh primeneniye v sistemakh avtomatizatsii proizvodstvennykh protsessov [Selsyns and Their Use in Systems for the Automation of Production Processes], Gosenergoizdat, 1962.

4. Aronov, Ya. I., Isayev, V. L., Patent No. 1899907, Byulleten' izobreteniy, No. 1, 1967.

5. Svecharnik, D. V., Patent No. 107434, Byulleten' izobreteniy, No. 8, 1958.